Helping Decision-Makers Select the Most Adequate Road Infrastructure Design from the point of view of Sustainability: A Practical Approach

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ABSTRACT

In recent years, a number of tools have been developed aimed at assessing the socio-economic and environmental feasibility of roadway projects. However, there is still no standardised or commonly accepted methodology to assure the most sustainable design in the appraisal and evaluation of roads over their life-cycle. The introduction of the multidimensional perspectives of sustainability in the appraisal of road projects is still an unresolved aspect. This research identifies strengths and weaknesses of sustainability assessment tools –including ratings systems, traditional decision-making techniques (e.g. cost benefit analysis, multicriteria decision analysis, among others), checklists and different evaluation frameworks and models for roadways; describes to what extent they integrate sustainability as a whole; and summarizes valuable lessons to learn from them. On the basis of this analysis, it points out a number of methodological issues that need to be addressed before valid road sustainability assessments can be conducted. To response to these issues, this research develops a composite decision support model based on combining cost-benefit analysis (CBA) with multi- criteria decision analysis (MCDA) to accurately appraise sustainability of road projects. This methodology is applied to a case study dealing with the construction of a new roadway in the northwest of Spain. The outcome demonstrates that the approach is a valuable sustainability assessment tool.

1. INTRODUCTION

Since the concept of sustainability reached international priority in the 1980s and 1990s, there has been a growth of interest in infrastructure sustainability concerns; see (Ashley & Hopkinson, 2002; Meyer & Jacobs, 2000; Rijsberman & van de Ven, 2000). However, as some authors admitted, despite sustainability becoming better understood in certain contexts, it is far from being a well-defined concept. Nevertheless, the need to achieve economic and social development and to protect the environment seems to be a general consensus. Although there are many approaches aimed at assessing the socio-economic and environmental feasibility of surface transportation projects such as roads and railway infrastructure, presently there is no standardised or commonly accepted methodology to assure sustainability in the appraisal and evaluation of road projects over their life-cycle. The literature available regarding sustainable infrastructure –see (Dasgupta & Tam, 2005; Gilmour, Blackwood, Banks, & Wilson, 2011; Tsai & Chang, 2012)– have claimed that there is an essential need by policy makers for practical tools and techniques to assess sustainability in all life stages of infrastructure projects.

Current approaches can be broadly grouped in two main categories. The first one includes the traditional decision-making techniques including cost-benefit analysis (CBA), multi-criteria decision analysis (MCDA), and others. The second one includes sustainability rating systems and models for assessing sustainability of infrastructure design and construction. None of these methods assess sustainability in a thorough way. Some of them are biased towards environmental or economic assessment whereas some others are overly focused on certain stages of project development.

There are two characteristics of this research which make it a new contribution to the state of knowledge. First, it develops a comparative analysis of current sustainability tools available for road projects in terms of their efficiency to drive sustainability efforts and the relative importance of their barriers in sustainability appraisal. And second, it develops a practical approach to introduce sustainability criteria in the appraisal of road projects. The proposed decision model consists of integrating the single criterion approach and the multiple criteria approach methodologies in tandem to fully address sustainability. The tool designed in this research is expected to help decision-makers select the most adequate road infrastructure design from the point of view of sustainability.

The document is structured in the following way. Section 2 summarizes the literature review regarding sustainability appraisal of road projects, and follows a systematic approach aimed at identifying key aspects that are not being incorporated in current methods and practices for sustainability assessment. Section 3 outlines the methodological approach. Section 4 discusses the results of the application of the proposed methodology to a case study. Finally, Section 5 establishes a set of conclusions, and final recommendations for additional research in this field.

2. LITERATURE REVIEW

2.1 Sustainability Concept

The history of the concept of Sustainability started in 1972 with the United Nations (UN) Conference on the Human Environment held in Stockholm, the first international symposium aimed at discussing exclusively environmental issues. Consecutively, the Brundtland Commission provided the most widely used of all definitions of sustainable development: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland World Commission on Environment and Development, 1987). Later, other important conferences and events associated with the UN Organization were held. By following all these conferences, it is possible to note that “there was a shift in the political debate from a primary emphasis on environmental issues, through a shared focus on environmental, social and economic development” (Paul, 2008).

In spite of this, until now there is not an acknowledged way to define sustainability. Most of these definitions are focused on specific fields for example economy, ecology, and environment (Gilmour et al., 2011; Parkin, Sommer, & Uren, 2003; Radermacher, 1999). Consequently, definitions tend to differ and “not a single reference presented a feasible definition of sustainable development which could incorporate all aspects of the concept commission’s report under investigation and provide no ideal understanding of this concept” (Ciegis, Ramanauskiene, & Martinkus, 2009). As Gilmour et al. (Gilmour et al., 2011) claimed, “it is generally accepted that the real challenge lies in understanding how to put it into practice: that is, to operationalise sustainability”.

2.2 Sustainability assessment: methods and techniques

Road infrastructure projects are appraised in practice through a number of tools or methodological frameworks including to a greater or lesser extent the concept of sustainability. Current methodologies can be grouped in two major categories:

1. The main appraisal tools for decision-making including CBA and the multiple criteria approach (MCDA). These tools do not address sustainability in a thorough way since they were not initially designed for that.
2. Rating systems (e.g. Greenroads, GreenLITES, Greenways) and models for evaluating sustainability of roads. Rating systems and certification tools “are typically produced by reputable governmental or non-governmental institutions, sometimes in collaboration with academia. They are intended to assess, compare and award a planned or existing facility, depending on its performance against relevant sustainability criteria” (International Federation of Consulting Engineers, 2012).

When examining how current highway-related sustainability methods and techniques work for the appraisal of sustainability, it is concluded that these methods are limited to certain sustainability drivers of road projects.

CBA is a known and widely used technique that enables the comparison among alternatives under a common and objective denominator. CBA offers valuable support since it is a rigorous, transparent and formal appraisal instrument. However, by examining the prospect of CBA application in promoting or demoting sustainable development it was found “abundant arguments disfavoring the application of CBA, represented by limitations such as: (i) trying to evaluate what are often not 'evaluatable,' i.e., non-economic values; (ii) limited considerations regarding distributional equity (including inter-temporal equity)” (Omura, 2004). Finally, one major criticism that has been brought to CBA as a sustainability tool is that it is not able to include the triple bottom line in a precise and narrow manner since the monetization process is questionable for some intangible items.

On the other hand, despite a number of authors have suggested that MCDA is the most appropriate tool to adopt decisions for sustainability appraisal (Janic, 2003; Tudela, Akiki, & Cisternas, 2006; Walker, 2010), the extensive study of multicriteria techniques for transportation projects has included issues that require further analysis. The main unresolved matter of this tool has to do with the aggregation of the individual criteria and transparency of judgements, usually called `the black box´ problem. Specifically, there are issues surrounding the use of weights and how these might be obtained in practice. The multicriteria approach provides a proper structure when tackling sustainability of transport projects, but the assessment process tends to become highly subjective and potentially ambiguous.

Rating systems are generally understood as useful tools whereby projects are ranked and scored against their sustainability performance. However, these approaches also have a number of weaknesses when dealing with the concept of sustainability. They lack transparency and objectiveness in the definition of criteria and selection of weights, which are not based on standardized methods of performance measurement (Lee, Edil, Benson, & Tinjum, 2010). Furthermore, they are mostly focused on environmental issues related to construction processes and materials and, in practice they are mostly used as `evaluation tools´ to certify projects already built rather than as `decision-making tools´.

Finally, several frameworks and models have been developed to provide guidance on the appraisal of infrastructure projects (e.g. ASPIRE and INDUS from the UK and Tamdem Empreinte from France); buildings (e.g. Sustainability Matrices from the UK); and transport projects (e.g. STAG from Scotland, WebTAG and Sustainability Decision Model –SDM– from the UK and the BE^{2}ST-in-highways^{TM} system from the US). These frameworks are useful for conducting an ex-ante evaluation of project alternatives, but most of them are based on subjective approaches with limitations similar to those listed for the MCDA. In addition, although in theory these models intend to evaluate project sustainability as a whole, in practice they mostly focus on environmental aspects. Moreover, even though social aspects are incorporated to a greater or lesser extent, they are not stressed in the analysis conducted by most of those tools.

3. DEVELOPMENT OF A DECISION MAKING TOOL TO ADDRESS SUSTAINABILITY

After strengths and weaknesses of sustainability assessment tools have been identified, and some of methodological issues have been revealed; this research develops a methodological approach to accurately appraise sustainability of road projects. This model is called STAR (Sustainability Tool for the Appraisal of Road Projects). This section presents the STAR methodology, aimed at assisting decision-makers and road designers to select the most suitable road infrastructure design alternative from the point of view of sustainability. The present method is structured in three steps; each one is described briefly in the following paragraphs.

3.1 Step 1 Identification of sustainability criteria and evaluation for each Alternative

Step 1 consists in identifying sustainability criteria and quantifying them for each alternative. Criteria can be grouped into different components of sustainability (economic/social/environmental). Depending on their specific characteristics, each criteria, will be evaluated for each alternative in quantitative—either monetary units or other units—or qualitative units. This phase is subdivided into three tasks. The following is a more detailed explanation of these tasks.

3.1.1 Task 1.A Identification of sustainability criteria over different project stages

Selecting appropriate criteria derived from sustainable requirements should not only focus on economic efficiency and environmental protection, but also on take into account the social aspects such as equity, which is ambiguously considered in current project appraisals. These criteria should be evaluated at each stage of the project (construction, maintenance and operation). Finally, in this step it is essential to detail those criteria which can be monetized, and which are to be measured in a qualitative way. Sustainability criteria have to be selected depending on the characteristics of the project that is being appraised. Hence the selection of items should be flexible enough as to accommodate the specific characteristics of each project. The table below summarizes a set of major sustainability items that may be considered for highway projects over their life-cycle.

Economic criteria	Environmental criteria	Social Criteria
Infrastructure costs	Energy consumption and CO_2 emissions	Community disruption
Travel Time	Habitat fragmentation and negative effects on species	Impacts on businesses and community services
Vehicle operating cost	Air pollution	Employment and Labour Standards
Accident cost	Noise pollution	Distributive effects of the project
Macroeconomic impacts	Landscape degradation/visual negative impacts	Occupational and community health and safety

Table 1 –Sustainability criteria for highway projects over the life-cycle

3.1.2 Task 1.B Quantification / qualification of sustainability criteria: identification of impacts for each alternative

In this stage, designers should quantify/qualify each sustainability criterion for each alternative to consequently obtain the specific project impacts. Decision makers should calculate the differential annual value (do-nothing scenario vs. do-something scenario) for each sustainability criterion. In particular, it is necessary to evaluate:

- Those impacts that can be quantified. Practitioners should quantify impacts in monetary units or other units. Particularly, for applying our methodology, we recommend that they use monetary values to appraise those items which have market prices that can be used as a good proxy of the social cost (e.g. investment costs, vehicle operating cost and maintenance/operation costs). However, we recommend using physical units for most of the criteria which are not bought and sold in the market (e.g. travel time savings, air/noise pollution, energy use, etc.).
- Those impacts that cannot be quantified should be evaluated through a qualitative approach based on the criteria of the decision maker. This research recommends the following "seven point assessment scale": **1** point if the impact is considered to be **highly negative**, **2** points if it is **moderately negative**, **3** points if it is **slightly negative**, **4** points if it is **neutral**, **5** points if it is **slightly positive**, **6** points if it is **moderately positive**, and **7** points if the impact is considered to be **highly positive (in comparison with the do-nothing scenario)**.

3.1.3 Task 1.C Inter-temporal aggregation of economic, environmental and social impacts

Based on the assumption that MCDA and CBA can be used in tandem, in this methodology we propose an alternative approach to discounting based on a different justification:

For those items that can be quantified and monetized with market prices (shadow prices available), future impacts can be converted to present day values (hereafter aggregated impacts *AI*) by using an appropriate discount rate. After aggregating impacts spread over time (i.e. after obtaining *AI*), *AI* should be translated into a qualitative seven point assessment scale −which can be interpreted as follows in Table 2− in order to obtain homogenized aggregated impacts (*HAI*). By using a homogenized scoring system rather than the monetized value, the cost benefit analysis can be merged in the multicriteria approach. However, since preference is not necessarily increasing with higher aggregated values, scale must be consistent by specifying an ordinal correspondence between criteria values and preferences, such as "more is better" or "less is better".

For those items that can be quantified and are not bought and sold in the market, the aggregation of these impacts is still controversial e.g. some authors suggest environmental discount rates, others apply monetary values and use traditional discount rates, while others claim for a simple aggregation despite impacts extend throughout a long period of time. We suggest keeping original units and not to discount these non-market goods. Accordingly, since there is no "well-known time preference", the *AI* should be obtained through a cumulative value to be converted from the original units, e.g. Tonnes of CO_2, into the seven point assessment scale -according to criteria shown in Table 2- in order to obtain the homogenized aggregated impacts (*HAI*).

And, for those items that cannot be quantified, similarly, the *AI* of qualitative impacts has no discounting technique. Aggregation should be encouraged by decision-makers through an average of scores (points allocated according to Task 1.B) over different time periods. The final score allocated to each alternative (i.e. the *HAI*) is given by the comparison of the *AI* of each alternative with the average *AI* of the project alternatives. Consequently, the seven point assessment scale can be interpreted for those items that cannot be quantified as shown in Table 2.

Points to assign (*HAI*)	Description	For a "Less is better" criterion	For a "More is better" criterion
		Numerical interpretation	Numerical interpretation
1 point	If the obtained *AI* of the alternative is **highly worse** than the average of the alternatives	AI>1.45*	AI<0.55*
2 points	If the obtained *AI* of the alternative is **moderately worse** than the average of the alternatives	1.30*<AI≤1.45*	0.55*≤AI<0.7*
3 points	If the obtained *AI* of the alternative is **slightly worse** than the average of the alternatives	1.15*<AI≤1.3*	0.7*≤AI<0.85*
4 points	If the obtained *AI* of the alternative is **similar** than the average of the alternatives	0.85*≤AI≤1.15*	0.85*≤AI≤1.15*
5 points	If the obtained *AI* of the alternative is **slightly better** than the average of the alternatives	0.7*≤AI<0.85*	1.15*<AI≤1.3*
6 points	If the obtained *AI* of the alternative is **moderately better** than the average of the alternatives	0.55*≤AI<0.7*	1.30*<AI≤1.45*
7 points	if the obtained *AI* of the alternative is **highly better** than the average of the alternatives	AI<0.55*	AI>1.45*

* times the average

Table 2–Seven point assessment scale for the AI

3.2 Step 2 Calculation of weights

Step 2 is aimed at determing the weights for the HAI obtained from Step 1. This step is based on a combination between the *Ratio Estimation in Magnitudes or deci-Bells to Rate Alternatives which are Non-DominaTed* system (REMBRANDT system), the Delphi method and an objective value defined as the *Level of Severity*. Then, the assignment of weighting coefficients to the sustainability criteria proposed in this method (resulting Task 2.E) is based on the project context (Task 2.A, Task 2.B and Task 2.C) and on evaluation judgments –preferences for pairwise comparisons of sustainability criteria- by decision makers and experts in the field (Task 2.D, related to experts judgments, irrespective of the context).

3.2.1 Task 2.A Evaluation of the present situation in the context of the project

The context of a project can be defined as the natural and socio economic environment in the project area. Since every project has a unique context, sustainability should be evaluated by understanding that it is context sensitive. In order to identify particularly sensitive aspects to the sustainability appraisal, this methodology intends to include all the natural, social and economic features of the area where the project is located. For that, the present situation (P_s) for each item needs to be considered in numerical values. Then, the analyst should compare these values with the average value of other similar contexts. Finally, a score has to be allocated to the present situation for each item in context is defined.

3.2.2 Task 2.B Evaluation of the trend

This task consists in evaluating the trend for each particular criterion in the geographical context where the project is going to be built. By making and justifying claims about tendencies in the data, analysts can establish the importance of each criterion for sustainability. The main outcome of the present task is the classification for each item trend as “improving”, “stable” or “worsening” and the allocation of the corresponding score (0 points, 1 point and 2 points, respectively).

3.2.3 Task 2.C Identification of the Level of Severity

The main purpose of Step 2 is to precisely establish sensitivity aspects with respect to the context. Levels of Severity (LS) for each particular item are obtained by summing up scores allocated in Task 2.A together with scores allocated in Task 2.B. Thus, the higher the LS the more sensitive the criteria will be in the context.

3.2.4 Task 2.D. REMBRANDT Technique and Delphi Method

Apart from context, to establish a trade-off between different criteria, it is also necessary to incorporate the preferences of decision-makers. To that end, a pair-wise comparison method aimed at determing the weights for every criterion is required. We recommend the REMBRANDT technique to derive weights since it is based on the well-known original *Analytic Hierarchy Process* (AHP). Furthermore, since consensus is rarely reached in practice, the Delphi technique should be used with the purpose of achieving a convergence of opinion from experts. The process can be completed throughout the following stages:

- Questionnaire design. Based on the previously identified list of sustainability criteria, pairwise comparisons should be organized. Then, experts should be asked to compare the importance of different sustainability criteria based on a -8 to +8 scale known as the REMBRANDT scale –see (Olson, Fliedner, & Currie, 1995).
- Application of the Survey: a number of experts for collaboration to complete the questionnaire should be selected. For this weighting exercise to be robust, a minimum of 30 responders is required.
- REEMBRANDT Calculations**:** for each surveyed expert, a matrix of preferences should be filled out. Each element of the matrix represents the preferences stated by the

expert. Then, by using the REEMBRANDT TECNIQUE, criteria weights should be obtained, –see Olson et al. (1995).

- Statistical Test: in order to evaluate the convergence of opinion for a weighting process to be deemed robust and valid, a statistical test should be conducted. We recommend a simulation based on a cross validation technique to estimate the level of consensus from the panel of experts. If the level of consensus is enough (p-values are less than 0.05) a Delphi method will not be necessary. In this case the average of weights obtained from the survey should be used as the Convergent Weights (CW).

Task 2.E. Sustainability criteria weights elicitation

For the final assignment of weighting coefficients to the sustainability criteria it is necessary to adjust obtained *CW* with the level of severity obtained from Task 2.C. In order to accomplish this goal, a Sustainability Weight (*SW*) for each sustainability criterion is calculated. The *SW* for the sustainability criterion *i* is defined according to equation (1).

$$SW_i = CW_i \ x \ LS_i \tag{1}$$

Where,

SW_i = Sustainability Weight for sustainability criterion *i*

CW_i = Convergent Weight for sustainability criterion *i*

LS_i = Level of severity for sustainability criterion *i*

3.3 Step 3 Sustainability Evaluations of Project Alternatives

This step intends to establish a procedure aimed at assessing road projects according to their sustainability performance.

Task 3.A Sustainability evaluation of project alternatives

Since at this stage of the methodology all economic, environmental and social items are expressed through homogenized aggregated impacts (*HAI*) on a seven point assessment scale, a sustainability evaluation should be conducted to obtain the ranking order of alternatives. We suggest a weighted sum method which is the most commonly used approach for these type of analysis. Then, the sustainability global evaluation of alternative *a* is calculated as shown in equation (2). The resulting score for each alternative can be used to rank and choose the alternative with the highest sustainability performance.

$$Sustainability\ Performance_a = \sum_{i=1}^{n} SW_i \ x \ HA_i \tag{2}$$

Where,

$Sustainability\ Performance_a$ = Sustainability performance of alternative *a*

SW_i = Sustainability weight for sustainability criterion *i*

HAI_i = Homogenized aggregated impact for sustainability criterion *i*

n = Total number of sustainability criteria of alternative *a*

The best alternative is the one with the highest score. However, the analyst should explore the potential compensation of impacts by developing a descriptive analysis in addition to the above process. It involves a comparison of each evaluation criteria across alternatives. After decomposing the *sustainability performance*, these results should be presented to decision-makers together with the global evaluation. Finally, decision-makers will be able to prioritize road alternatives on a sustainable basis. The effective incorporation of all sustainability issues in the decision making process can thus be assured.

4. PRACTICAL APPLICATION OF THE METHODOLOGY

To demonstrate the feasibility and usefulness of the proposed methodology, in this section we apply it to a case study dealing with the construction of a hypothetical new interurban roadway in the northwest of Spain. Three alternative routes will be considered in this study.

4.1 Description of the case study

The criteria we adopted to evaluate the sustainability performance of the alternatives as well as the main project characteristics are included in detail in Table 3.

4.2 Results for Step 1

This section discusses the applicability of the developed methodology for Step 1. At this stage of the case study we adopted some general assumptions for the analysis. The identified list of sustainability criteria that should be considered when appraising sustainability for the evaluated project is shown in Table 4. We used monetary values to appraise investment costs, vehicle operating costs and road maintenance/operation costs. Some criteria that do not have market prices—travel time savings, energy and fuel consumption, CO_2 emissions, road accidents—will be measured in physical units. The remaining criteria will be measured in qualitative terms.

On the basis of values provided by Table 3 and in order to obtain the specific project impacts, each sustainability criterion was quantified for alternative 1, 2, and 3. For all the identified sustainability criteria, the differential annual value was calculated (do-nothing scenario vs. do-something scenario). All calculations were made over the appraisal period that is assumed to be 25 years.

For alternative 1, alternative 2, and alternative 3 each sustainability criterion was aggregated to obtain a present value to be translated into the seven point assessment scale. For all the identified sustainability criteria with market prices, we used a cost benefit analysis framework to convert future impacts to present day values. Regarding those items without good market prices, we did not discount these goods, and then we obtained a present day value through a cumulative value. Finally, we classified each item as a “more is better” criterion or a “less is better” criterion and on the basis of Table 2 we obtained homogenized aggregated impacts (HAI) –see Table 4.

Project Characteristic	Alternative 0 do-nothing scenario	Alternative 1 do-something scenario 1	Alternative 2 do-something scenario 2	Alternative 3 do-something scenario 3
General description	Existing road. Traffic safety, operation conditions and capacity should be improved.	Road widening. The existing road width is not adequate for the traffic, and extra lanes are needed.	Maintain the existing road and construct a new motorway (located on the north of the existing road)	Maintain the existing road and construct a new motorway (located on the south of the existing road)
Length (m)	40	40	37	30
Vehicle operating costs (€ veh/Km)	0.18	0.12	0.15	0.10
Maintenance cost (€/Km)*	18,000	30,000	30,000	40,000
Operation cost (€/Km)	12,000	20,000	20000	30,000
Investment (million €/Km)	0	2.0	2.5	4.0
AADT (veh/daily)	16,000	18,000	18,000	18,000
Accidents (accidents/million veh*km)	1.0	0.8	0.6	0.2
Travel Time (min)	32	22.4	20.7	16.7
Habitat fragmentation and negative effects on species		Neutral **	Highly negative**	Slightly negative**
Landscape degradation/visual negative impacts		Neutral**	Neutral**	Neutral**
Noise pollution		Moderately negative**	Highly negative**	Highly negative**
Employment effects		Highly positive**	Highly negative**	Highly negative**
Community disruption		Slightly negative**	Highly negative**	Moderately negative**
Impacts on businesses and residents		Slightly negative**	Highly negative**	Moderately negative**
Social and distributional impacts		Slightly positive**	Neutral**	Neutral**

* Including periodic and extraordinary maintenance ** In comparison with the do-nothing scenario

Table 3 – Characteristics of the project alternatives

Sustainability Criterion	Type of Criteria	Alternative 1 (HAI)	Alternative 2 (HAI)	Alternative 3 (HAI)	Level of Severity	POINTS
Investment costs	Less is better	5	4	3	6	
Maintenance costs	Less is better	7	3	2	6	
Road operation cost	Less is better	7	4	2	6	
Vehicle operating cost savings	More is better	5	1	6	6	
Road accidents savings	More is better	1	4	7	6	
Travel time savings	More is better	4	4	4	2	
Energy consumption	Less is better	6	2	4	2	
Fuel consumption	Less is better	6	2	4	3	
CO2 emissions	Less is better	5	2	4	1	
Habitat fragmentation and negative effects on species	More is better	7	1	4	6	
Landscape degradation/visual negative impacts	More is better	4	4	4	6	
Noise Pollution	More is better	7	3	3	4	
Community disruption	More is better	7	1	4	6	
Impacts on businesses and community services	More is better	7	1	4	6	
Employment effects	More is better	7	1	1	7	
Social and distributional impacts	More is better	5	4	4	5	

Table 4 – Aggregated impacts for all the alternatives (Step 1 results) and level of severity for each particular item (Step 2 results)

4.3 Results for Step 2

Since the methodology is applied to a case study dealing with the construction of a new roadway in the northwest of Spain, we conducted an evaluation of the present situation and the trend for this particular geographical area where the project is located. Consequently, we allocated a score to the present situation for each criterion in context. Furthermore, after classifying trends for each particular criterion, a score was allocated to each attribute trend. Finally, the Level of Severity was obtained –see Table 4.

Based on the previously identified sustainability criteria list, we organized pairwise comparisons by asking 32 experts to complete a questionnaire aimed at determing priorities among different criteria related to roadways over their life cycle. On the basis of their personal view regarding the relative importance of the economic, environmental and social criteria defined for this analysis, we obtained criteria weights. Final results from the weighting exercise are shown in Table 5 (see the "Criteria Weight" column). According to preferences of decision-makers, accident cost savings is strongly preferred over other economic criteria. For environmental and social criteria differences were not that significant.

On the basis of the information obtained, we estimated the level of consensus from the panel of experts by using a statistical test founded on a cross validation technique. In brief, the data of the surveyed experts (criteria weights) were divided into two equal-sized parts. Then, the test compared the answers of both groups in order to find significant differences. This procedure was repeated 1000 times, with randomly selected groups. The result was a p-value distribution for each sustainability criterion. According to these results, we observed reported p-values lower than 0.05. Consequently we were able to conclude that the level of consensus is good enough so a Delphi method is not necessary. Subsequently, we adjusted obtained Convergent Weights (*CW*) with the level of severity obtained from Task 2.C. Finally a Sustainability Weight (*SW*) for each sustainability criterion was calculated by applying equation (1). Results are also shown in Table 5.

Sustainability Component	Sustainability Criterion	Criteria Weight	Normalized weight	Sustainable weights	Normalized Sustainable weights
Economic	Investment costs	1.15	3.820	22.92	4.516
	Maintenance costs	1.5	3.820	22.92	4.516
	Road operation costs	1.15	3.820	22.92	4.516
	Vehicle operating costs	0.96	3.215	19.29	3.802
	Accident costs	4.36	14.523	87.14	17.170
	Travel time	1.24	4.136	8.27	1.630
Environmental	Energy consumption	1.62	5.411	10.82	2.133
	Fuel consumption	1.62	5.411	16.23	3.199
	CO2 emissions	1.62	5.411	5.41	1.066
	Habitat fragmentation and negative effects on species	1.65	5.490	32.94	6.491
	Landscape degradation/visual negative impacts	1.79	5.951	35.70	7.036
	Noise Pollution	1.70	5.658	22.63	4.460
Social	Community disruption	2.52	8.412	50.47	9.945
	Impacts on businesses and community services	2.68	8.942	53.65	10.572
	Employment effects	2.44	8.129	56.91	11.213
	Distributive effects of the project	2.35	7.850	39.25	7.734

Table 5 – Summary of the weighting process

4.4 Results for Step 3

For each alternative we conducted the sustainability evaluation. In summary, we used the weighted sum method to obtain the ranking order of alternatives (equation 2). The sustainability global evaluation of all alternatives was obtained in order to choose the alternative with the highest sustainability performance. As Figure 1 shows, alternative 1 is the option with the largest area. This suggests that this is the best alternative from the sustainability standpoint.

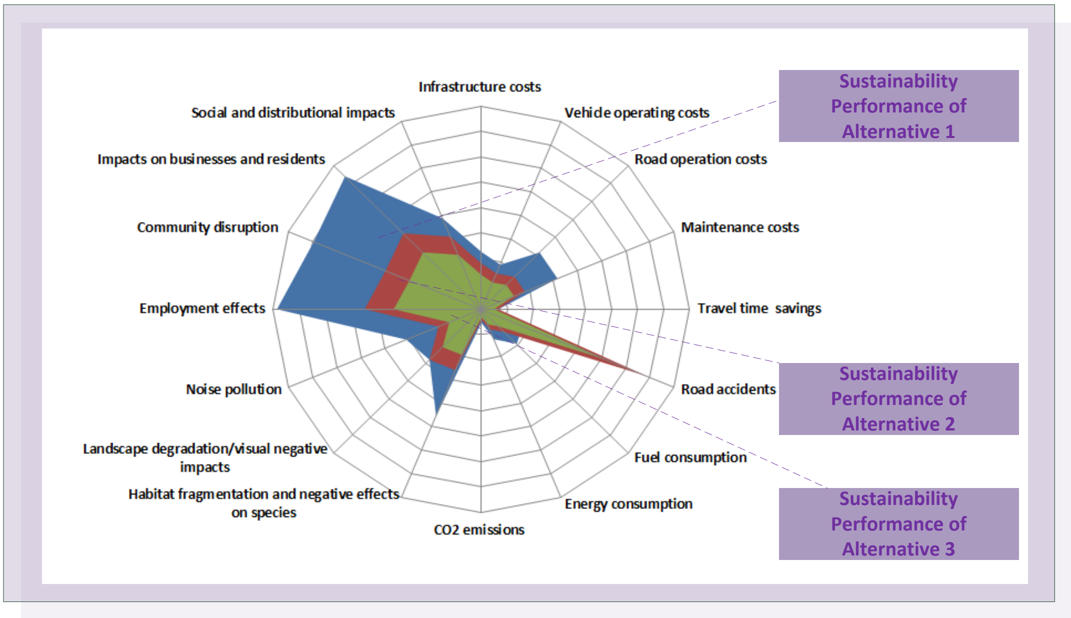

Fig. 1 –Radar Chart: sustainability performance for the alternatives

5. CONCLUSIONS

Although the concept of sustainability has reached prominence, incorporating sustainable concepts into the decision-making process is still an unresolved matter. Despite the numerous sustainability tools available, none of them seems to address sustainability as a whole. While there are positive characteristics associated with each tool, some practical issues remain unsolved. On the basis of the gaps identified in the literature, we were able to point out a set of essential requirements for sustainability assessment of roadways. The sine-qua-non requirements for a tool to become suitable when appraising sustainability of road projects are the following:

- Requirement number 1 (Life-cycle approach): Sustainability appraisal tools (SATs) should be based on a life-cycle perspective and they should be able to capture all the sustainability impacts over the lifespan of the road infrastructure, from conception through construction, operation and maintenance.
- Requirement number 2 (Full approach): SATs should take into account all the criteria that in a way or another may influence sustainability including equity over generations.
- Requirement number 3 (Rigorous trade-offs): SATs should use analytical and rigorous mechanisms for comparing all trade-offs among economic, environmental and social aspects. Understanding trade-offs allows a full comprehension of the sustainability concept since it implies a clear representation of the extent to which the worsening of one sustainability item might be offset by the improving of another one.
- Requirement number 4 (Transparent approach): SATs should be transparent, rational and formal instruments in order to minimize ambiguity and ensure consistency and accuracy. The more rigorous the tool the better the control of systematic bias, and the

higher its acceptability for academics and practitioners.

- Requirement number 5 (Adaptability to the context): SATs should be able to identify the particular relevance of each sustainability item within the specific characteristics of the social and geographical context where the project is located.

On the basis of the previously identified prerequisites for a tool to become suitable when appraising sustainability, this study has developed a methodological approach to accurately appraise sustainability of road projects. The model is called STAR (Sustainability Tool for the Appraisal of Road Projects) and it consists of integrating the single criterion approach and the multiple criteria approach methodologies in tandem to fully consider sustainability. The novelty of the described methodology resides in the way that it retains the strengths and addresses the weaknesses of the CBA and the MCDA technique.

Finally, the model was applied to a case study dealing with the construction of a new roadway in the northwest of Spain. The application of the methodology to this case study allows us to validate the model outlined in the research. The case study shows the feasibility of model and the results show the potential advantage of the proposed method in the sustainability appraisal framework.

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